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Another method for specifying furanose ring puckering

Tomohiro Sato

Shionogi Research Laboratories, Shionogi and Co., Ltd., Fukushima-ku, Osaka 553, Japan

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ABSTRACT

A set of pseudorotation coordinates is proposed for characterizing the puckering of the furanose ring. These are defined from the curvilinear displacements of the C1' and C4' atoms from the planar conformation. The present coordinates have some practical advantages over the ones currently used.

INTRODUCTION

The significance of the sugar conformation has been well recognized in the structural study of nucleic acids. Energy calculations[1,2] and various puckers as revealed by X-ray analysis indicate that the potential surfaces of both the ribose and the deoxyribose rings have low-energy paths more or less similar to the one found with cyclopentane, which is known to undergo a 'pseudorotation'.[3]

The puckering of 5-membered rings in general can be described by two out-of-plane displacement modes, bending (z_1) and twisting (z_2), from the planar conformation.[4] In the case of a molecule displaying pseudorotation, it is more convenient to use a polar representation (r, ϕ), $z_1 = r\cos\phi$ and $z_2 = r\sin\phi$, because the r value remains nearly constant along the low-energy path. Pseudorotation coordinates such as r and ϕ should be useful for characterizing the sugar puckering.

The first attempt along this line was done by Altona and Sundaralingam.[5] They noticed that the values of the five ring torsion angles θ_j $(j = 0,1,\cdots,4)$ could be approximated as

$$\theta_j = \theta_m \cos(P + 144^\circ j), \tag{1}$$

and, based on these equations, proposed a method for calculating

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the pseudorotation parameters, θ_m and P, from a given set of the torsion angles:

$$\tan P = \frac{\theta_2 + \theta_4 - \theta_1 - \theta_3}{2\theta_0(\sin 36^\circ + \sin 72^\circ)} \tag{2}$$

$$\theta_m = \theta_0 / \cos P \tag{3}$$

Although these parameters have been widely used, this definition has a drawback. Since the relationships in (1) are only approximate and, therefore, cannot be used to calculate the ring torsion angles, the pseudorotation parameters by themselves do not specify explicitly any structural quantities about the ring conformation. A recent modification[6] of the Altona-Sundaralingam definition did not overcome this inconsistency.

Cremer and Pople[7] devised a method for finding a unique mean plane of a given pucker such that the rectilinear displacement of the j-th ring atom from the plane was expressed as

$$z_j = (2/5)^{1/2}\, q \cos[\phi + 4\pi(j - 1)/5] \tag{4}$$

These equations retain the same functional form that Kilpatrick *et al.*[3] invented to describe a pseudorotation with an ideally small amplitude in cyclopentane, and can be applied to any 5-membered ring with a large puckering and heteroatoms. The relationships in (4) are rigorous in contrast to (1) and, therefore, can be used without contradiction to generate various puckers specified by the pseudorotation coordinates q and ϕ.[8] However, this process involves tedious calculations, mainly because use of the rectilinear displacements in (4) gives rise to a change in the bond distances on varying the pseudorotation coordinates. Since the mean plane defined by Cremer and Pople does not have much meaning in nuleic acid chemistry, it would be desirable to avoid such a complication if possible.

This paper attempts to define pseudorotation coordinates by means of the curvilinear displacements which have been used to conveniently calculate the energy of sugar rings.[9] These coordinates may be suitable for studying ring puckering with a large amplitude since the bond distances remain constant even when they are changed much.

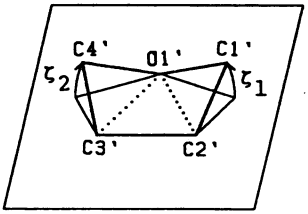

Fig. 1. A schematic view of the furanose ring showing the curvilinear displacements of C1' and C4' atoms from the planar conformation with their signs.

METHODS

Considering the approximate C_{2v} symmetry of the planar furanose ring, we use the curvilinear displacements of C1' and C4' atoms from the planar conformation. Namely, they are

ζ_1 = the dihedral angle between the planes (O1', C1', C2') and (O1', C2', C3')

and

ζ_2 = the dihedral angle between the planes (O1', C4', C3') and (O1', C2', C3').

The positive signs of these angles are indicated in Fig. 1 [see also (9) and (10).

As the quantities $(\zeta_1 + \zeta_2)$ and $(\zeta_1 - \zeta_2)$ correspond to the bending and twisting modes, respectively, we define

$$z_1 = \cos(\pi/5)(\zeta_1 + \zeta_2) \tag{5}$$

$$z_2 = \sin(\pi/5)(\zeta_1 - \zeta_2) \tag{6}$$

$$\Pi = (z_1^2 + z_2^2)^{1/2} \tag{7}$$

$$\Phi = \tan^{-1}(z_2 / z_1) \tag{8}$$

The proportional constants employed in (5) and (6) were introduced in order to locate the ten envelope forms nearly at equal intervals in respect to the phase angle Φ (Fig. 2).

When the atomic coordinates are known, for example, from X-ray analysis, the pseudorotation coordinates can be conveniently obtained using usual crystallographic routines to calculate the improper torsion angles C1'-O1'-C2'-C3' (τ_1) and C4'-O1'-C3'-C2' (τ_2), which can be then converted into the angles ζ_1 and ζ_2:

$$\zeta_1 = 180^\circ - \tau_1, \quad 0 < \tau_1 < 360^\circ \tag{9}$$

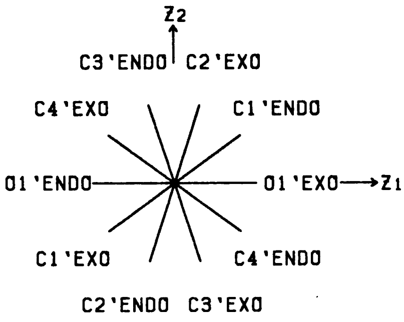

Fig. 2. Pseudorotation cycle showing the ten envelope forms together with the bending (z_1) and twisting (z_2) axes.

$$\zeta_2 = \tau_2 - 180^\circ, \quad 0 < \tau_2 < 360^\circ \tag{10}$$

The standard deviations of the pseudorotation coordinates can be estimated from those in the improper torsion angles:

$$\sigma(\zeta_i) = \sigma(\tau_i) \tag{11}$$

$$\sigma^2(z_1) = \cos^2(\pi/5)[\sigma^2(\zeta_1) + \sigma^2(\zeta_2)] \tag{12}$$

$$\sigma^2(z_2) = \sin^2(\pi/5)[\sigma^2(\zeta_1) + \sigma^2(\zeta_2)] \tag{13}$$

$$\sigma^2(\Pi) = (1/\Pi^2)[z_1^2\sigma^2(z_1) + z_2^2\sigma^2(z_2)] \tag{14}$$

$$\sigma^2(\Phi) = (1/\Pi^4)[z_2^2\sigma^2(z_1) + z_1^2\sigma^2(z_2)] \tag{15}$$

Various puckers specified by the pseudorotation coordinates can be constructed when the remaining degrees of freedom are specified by the five bond distances and two bond angles O1'-C1'-C2' (α_1) and O1'-C4'-C3' (α_2). The positions of O1', C1', C2', C3' and C4' atoms in a cartesian coordinate system are calculated respectively as

$$(0, 0, 0),$$

$$(r_1\cos\beta_1, r_1\sin\beta_1\cos\zeta_1, r_1\sin\beta_1\sin\zeta_1),$$

$$(a_1, 0, 0),$$

$$(a_2\cos\gamma, -a_2\sin\gamma, 0)$$

and

$$(r_5\cos\beta_2 \cos\gamma - r_5\sin\beta_2\cos\zeta_2\sin\gamma, -r_5\cos\beta_2\sin\gamma$$
$$- r_5\sin\beta_2\cos\zeta_2\cos\gamma, r_5\sin\beta_2\sin\zeta_2),$$

where

$$\zeta_1 = \Pi \sin(\Phi + \pi/5)/\sin(2\pi/5) \tag{16}$$

$$\zeta_2 = -\Pi \sin(\Phi - \pi/5)/\sin(2\pi/5) \tag{17}$$

$$a_1 = (r_1^2 + r_2^2 - 2r_1 r_2 \cos\alpha_1)^{1/2} \tag{18}$$

$$a_2 = (r_4 + r_5 - 2r_4 r_5 \cos\alpha_2)^{1/2} \tag{19}$$

$$\cos\beta_1 = (a_1^2 + r_1^2 - r_2^2)/(2a_1 r_1) \tag{20}$$

$$\cos\beta_2 = (a_2^2 + r_5^2 - r_4^2)/(2a_2 r_5) \tag{21}$$

$$\cos\gamma = (a_1^2 + a_2^2 - r_3^2)/(2a_1 a_2) \tag{22}$$

and r_1, r_2,•••, r_5 denote the distances of O1'-C1', C1'-C2',•••, C4'-O1' bonds, respectively.

EXAMPLE AND DISCUSSION

Clearly from the definition, the ring conformations having $\Phi = 36, 144, 216$ and 324° are the exact envelope forms of C1'-endo, C4'exo, C1'exo and C4'endo, respectively, where the pseudorotation amplitude, Π, measures the dihedral angle which the plane formed by the puckered atom and its neighbors makes to the plane of the planar four atoms. However, this interpretation is approximate for the other envelope forms, because of the asymmetry in taking the curvilinear displacements. An exact envelope form of C3'endo with the dihedral angle of 34.7° (the atomic coordinates are given in Table 1), for example, is expressed as $(\Pi, \Phi) = (35.7^\circ, 107.4^\circ)$. [The same pucker has the pseudorotation parameters $(\theta_m, P) = (35.3^\circ, 18.5^\circ)$ in the old Altona-Sundaralingam notation[5] and $(36.1^\circ, 18.2^\circ)$ in the new one.[6]] According to this example, the interpretation that the ten envelope forms are located at equal intervals of 36° in Φ is reasonable, because, if so, C3'endo puckers should have had $\Phi = 108^\circ$.

Table 1. Atomic coordinates of an exact envelope form of C3'endo in a cartesian system (Å).

	x	y	z
O1'	0.0	0.0	0.0
C1'	1.1189	0.8007	0.3304
C2'	2.3680	0.0	0.0
C3'	1.8728	-1.4424	0.0
C4'	0.4513	-1.2738	-0.5257

The relationships between the present and the Altona-Sundaralingam notations can be written roughly as

$$\Phi \simeq P + 90^{\circ} \tag{23}$$

$$\Pi \simeq \theta_m \tag{24}$$

The difference of 90° in (23) seems to be confusing, but the present notation is convenient for various Φ-plottings ($0 \leq \Phi < 360^{\circ}$), because it locates the unstable O1'exo puckers at $\Phi = 0^{\circ}$.

The conformation of sugar rings can be described in a number of ways, but the pseudorotational description is clearly very useful. The pseudorotation coordinates introduced in this paper satisfy the fundamental requirements for such quantities in a direct manner.

Recently, the torsion angle O3'-C3'-C4'-C5' was used to describe the sugar puckering.[10] This method is based on the assumption that the torsion angle is directly related to the pseudorotation angle. However, this is not always correct, because in the vicinities of C3'endo-C4'exo and C3'exo-C4'endo, for example, the torsion angle is not sensitive to a change in the phase angle but to one in the amplitude.

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